Effect of Bridges' Width on Optimum Design of Steel Bridges

Firas Ismael Salman*1, Abdul Muttalib Issa Said[2]

*1, 2 Department of Civil Engineering, College of Engineering, University of Baghdad, Iraq.
Jadriyah, B.O. box 47024, Fax 009741 7782050, Baghdad, Iraq

*1firasslmn@yahoo.com; [2]abdmusawi@yahoo.com

Abstract

This paper presents the effect of the bridge's width on the optimum design of steel bridges. I-section is considered for main girders and diaphragms. The problem of optimum cost of steel bridges is formulated as minimization of initial cost (IC) which consists of substructure cost and superstructure cost. The performance constraints in the forms of deflection, stresses, local buckling etc, are based on the *AASHTO* Specifications. The Sequential Unconstrained Minimization Technique (*SUMT*) is used to make required optimizations for costs. Orthotropic plate theory is introduced to analyse the bridge system.

To demonstrate the effect of widths on the optimum design of bridges, a steel I-girder bridge with various lengths and widths were chosen. From the results of the numerical investigation and figures, it may be positively stated that the optimum design of steel I-girder bridges based on SUMT technique in this study will lead to more reasonable, economical design compared with conventional design.

The main results found from this study [For bridges less than 350 m length] are that (1) There is an insignificant effect of the bridge's width on the ratio of substructure cost/ superstructure cost. (2) The number of girders required for a bridge to give optimum design ranges from two to four girders.

Keywords

Optimum Design; Steel Bridges; I-girder

Introduction

Generally, the objective of structural design is to select member sizes with the optimal proportioning of the overall structural geometry so as to achieve minimum initial cost design that meets the performance objectives specified in the conventional design specification. In the optimum design procedure, the objective function of a number of variables, is to be minimized, considering all the constraints. Samuel and Muhammad, 1980; used four variables and found the thicknesses of web and flange in the range of local buckling constraints. Farkas, 1984; found that the thickness of web and flange depended mainly on local buckling constraints and used only two variables that are the width and depth of the I- section for the formulation of the problem. In the present study, the thicknesses of web and flange of I-sections are used as dependent variables and limited by the thicknesses obtained from local buckling constraints; and that the optimum ratio of web area A_w to the total cross-section area (A_w/A), which gives maximum section modulus and maximum moment of inertia is equal to 0.5 and 0.75 respectively for both I and box-sections, where ($A=A_w+A_f$).

For I-section beams, (without stiffeners for web), Schilling, 1974; found that the optimum ratio of (A_w/A) to be (0.5) for elastic stress and (0.75) for optimum stiffness for deflection control, as well that for a beam with (A_w/A) ratio of (0.39) and (0.62), the elastic bending strength is within 98% of the maximum possible strength. At (A_w/A) ratio of (0.63) the elastic strength and stiffness are both about 97.5% of their maximum possible values.

The scope of this study is to prepare design charts by building a computer program, which computes the optimum number of girders, diaphragms, piers, depth both of girders and diaphragms required for optimum design of steel I-girder bridges based on initial cost for various widths of bridges. So this program examines all the possible probabilities (including number of piers) to find the optimum design, while in the previous studies, the optimization results came for bridges with certain number of piers and girders. Also this program optimizes both of substructure and infrastructure for the bridges. The width of the bridge is one of the factors which effect the bridge's design and cost. Right angle deck slab and simply supported girders used in this study.

Formulation of Optimum Design Problem

The bridge consists of RC deck slab, main steel girders, diaphragms, and RC piers. The piers are supported by foundations that consist of piles and pile caps. The

optimization problem is formulated with two variables, the depth of main girders and that of diaphragms. Thus, the optimization problem is formulated by considering the initial total cost for the bridge system hence the Sequential Unconstrained Minimization Technique (SUMT) can be also introduced to make these optimizations.

Design Variables

The design consists of two variables, as mentioned before. The first variable (x_1) represents the depth of main girders and the second variable (x_2) represents the depth of diaphragms. Many relations among the two variables and the dimensions of the steel sections have been derived.

One of the assumption used in this study was Schilling (1974) for I-section beams, which used (A_w/A) ratio equal to 0.63 to obtain ratios for the elastic strength and stiffness being both about 97.5% of their maximum possible values.

The other dependent variables are web depth (h), web thickness (t_w), flange width (b_f) and flange thickness (t_f) for both girder and diaphragm sections.

Objective Function

As mentioned previously, it is shown in this paper that the design goal is to minimize the total expected initial cost that can be divided into substructure and superstructure cost.

This cost can be formulated as follows:

Total Cost = Substructure Cost+ Superstructure Cost.

$$C_{total} = C_{sub} + C_{super} \qquad (1)$$

FIG. 1 and FIG. 2 show various sections in a composite RC deck on I-girder Bridge. The bridge is simply supported above two piers or more. The main girders and diaphragms are I-steel sections.

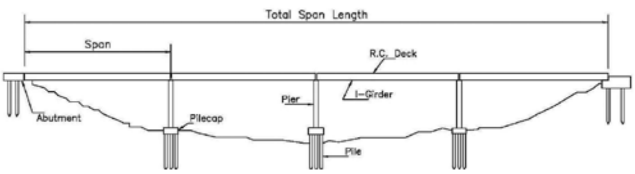

FIG. 1 LONGITUDINAL SECTION FOR SIMPLY SUPPORTED BRIDGE

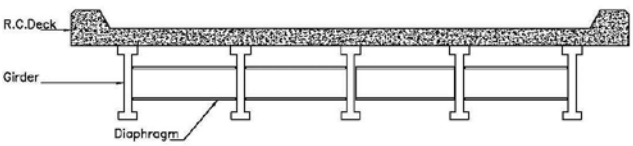

FIG. 2 TYPICAL CROSS-SECTION IN COMPOSITE STEEL I-GIRDRD BRIDGE

Constant Relations in the Bridge System

The bridge consists of concrete deck slabs, build-up I-section for main girders and for diaphragms, and concrete piles and piers.

In this study, American Association of State Highway and Transportation Officials (*AASHTO*), 1989 is used for bridge loads and constraints. The designed live loading has been assumed to give the worst effect of HS20 and Equivalent Load for both directions of the deck.

The following assumptions have been used to prepare this study:

- Deck concrete Strength Grade is 25 MPa.
- Superimposed dead load is 50 mm of asphalt, uncontrolled with load factor.
- Deflection under HS20 loading with spacing between rear axles equals to 4.27 m is limited to Span/800.
- Girders are composite for all loads.
- Bearing capacity of piles are 40 tons.
- Deck slab thicknesses, as shown in TABLE 1 below:

TABLE 1 THICKNESS OF REINFORCED CONCRETE DECK SLAB

Girder Spacing (mm)	Deck Slab Thickness (mm)
1700 -2200	180
2800	200
3500	220

Results were studied to investigate the influences of steel grade, cost ratio of materials, bearing capacity for piles, width and length of the bridge.

The constant relations used in this study are: -

(a) Span length=Total Length/(Number of Piers–1) (2)

(b) Spacing between girders (SPG),

$$SPG = \frac{\text{Width of bridge}}{(\text{No. of girders} - 1)} \qquad (3)$$

(c) Spacing between diaphragms (SPD),

$$SPD = \frac{\text{Total Length}}{(\text{No.of diaphragms} - \text{No.of piers} + 1)} \qquad (4)$$

(d) According to AASHTO [Clause 1.7.21]

Max. spacing between 2 diaphragms≥7.55 m (25 ft) (5)

And, for each span, Minimum number of diaphragms =3

No. of Diaphragms for each span,

$$NODES = \frac{\text{Total No. of diaphargms for bridge (NOD)}}{(\text{No.of piers} - 1)} \qquad (6)$$

No. of diaphragms for each span – 3.0>0 (7)

(e) For each bridge, minimum number of piers=2 (8)

(f) Minimum Number of Main Member = 2, AASHTO

[Clause1.7.22] (9)

(g) According to AASHTO [Clause 1.5.27], slab thickness (t_s) must be not less than 0.165 m (0.542 ft) for continuous span; and that for simple span should have about 10% greater thickness, in which (t_s) is not less than 0.180 m, thus:

$$t_s \geq 0.180 \tag{10}$$

The Constraints

1) Behaviour Constraints

(i) Deflection:

Maximum deflection occurring at mid-span of the girder must be less than or equal to the maximum allowable deflection. According to AASHTO [Clause 1.7.12], the deflection due to live load plus impact shall not exceed 1/800. All bridges in this study are simply supported, thus:

$$\Delta_{all} > \Delta_{\max} \Rightarrow \Delta_{all} - \Delta_{\max} > 0 \tag{11}$$

$$\Delta_{all}(mm) = \frac{span \times 1000}{800} \tag{12}$$

(ii) Stresses

Girders subjected to bending stresses shall be proportioned to satisfy the following requirements.

$$F_b > \frac{M_x}{S_x} \quad \text{where } F_b = 0.60\ F_y \tag{13}$$

(iii) Local Buckling of Flanges

The local buckling constraint for the compressed flanges of I-structural sections of uniform thickness subjected to bending or compression is given by AASHTO [Clause 1.7.6]:

$$\frac{b_f}{t_f} > \frac{3250}{\sqrt{f_b}} \text{ for girders} \tag{14}$$

2) Side Constraints

(i) Ratio of Depth to Length

AASHTO [1.7.10] stated that for girders the ratio of depth to length of span, preferably shall not be less than 1/25, and for composite girders the ratio of depth of steel girder alone to length of span shall not be less than 1/30.

$$\frac{Length\ span}{Depth} < 25 \text{ if non- composite} \tag{15}$$

$$\frac{Length\ span}{Depth} < 30 \text{ if composite} \tag{16}$$

(ii) Depth of Diaphragm

AASHTO [clause 1.7.21] stated that diaphragms shall be at least 1/3 and preferably 1/2 the girder depth.

$$\frac{Diaphragm\ depth}{Girder\ depth} > \frac{1}{3} \tag{17}$$

(iii) Minimum Thickness of Web

AASHTO [1.7.13] indicated that the thickness of web shall be not less than 8 mm (5/16 in). Here in this study, minimum thickness of web plate (t_{WG}) used = 10 mm.

AASHTO [Clause 1.7.70] stated that the web plate thickness of plate girders without longitudinal stiffeners shall not be less than that determined by:

$$\frac{X_1\sqrt{0.145 f_{b1}}}{23000} \tag{18}$$

Where X_1= Depth of Main Girder, and f_{b1} in kPa. Thus the thickness shall not be less than the depth of main girder divided by specified value, (*Coef*2); and this value is found according to yield strength for the girder F_y. This is shown in Equation (19):

$$Coef\ 2 = \frac{23000}{\sqrt{0.145 * 0.6 * Fy}} \tag{19}$$

$$\mathbf{t}_{WG} = \frac{\text{Depth of Girder}}{Coef\ 2} \tag{20}$$

By the same way, and if the diaphragm has same F_y the thickness of web plate for it equals:

$$\mathbf{t}_{WD} = \frac{\text{Depth of diaphragm}}{Coef\ 2} \tag{21}$$

(iv) Minimum Thickness of Slab

According to AASHTO [Clause 1.5.27][1], minimum thickness of slab equals:

$$D\min_{(m)} = 0.1 + \frac{Spacing\ between\ girders}{30}$$

But not less than 0.165 m (22)

Where Spacing in meters.

Computer Program for Structural Analysis and Optimization (CPSAO)

A computer program is written using FORTRAN 77. In addition to the main computer program, several subroutines have been written and one subroutine has been developed to satisfy constraints that may control the design process.

The program has been tested; and Microsoft Developer Studio-Fortran Power Station 4.0 Compiler was used in compilation, linking and creating an execution file for computer program for structural analysis and optimization (CPSAO). The linking process has been made for the main program and subroutines. FIG. 3 shows the detailed flow chart for the main computer program.

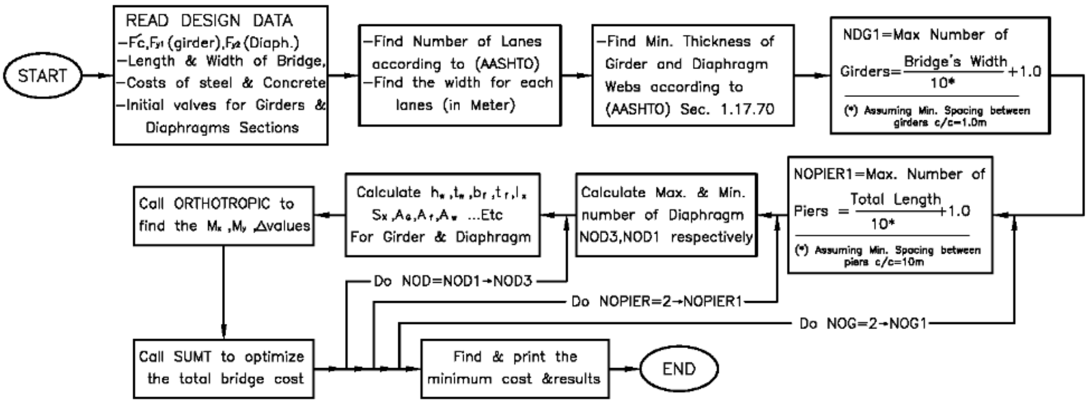

FIG. 3 DETAILED FLOW CHART FOR THE MAIN PROGRAM.

A computer program for the analysis of structural systems was built by using orthotropic plate theory and for the optimum design by using SUMT. The main objective of the program is to analyse and find the optimum design of I-girder steel bridges with minimum cost. With this objective the program was developed in such a way that a routine can be added for any type of bridges without disturbing the main program.

The program is organized to analyse bridges using different span, width and cost ratio by using three loops. The various routines that constitute the core of the program CPSAO are explained in the following sections.

Applications and Discussion of Results

The optimum design of two-dimensional bridge is studied by using four applications for the width of steel I-girder bridges. The widths used were 4 m, 7 m, 10 m, and 13 m respectively. The effect of bridge's width on the cost and on other parameters was studied.

A sample of results was given in this paper for bearing capacity of piles 40 tons, yielding strength for steel used in girders and diaphragms = 358 MPa and Cost Ratio CR = 6. The CR represents the cost for one ton of steel divided by the cost for one meter cubed of reinforced concrete.

Discussion of Results

Structural optimization means producing a design with structural section minimum size or weight (based on the objective function prepared for each case) can be formulated in certain mathematical models. The acceptance of an optimum solution from a practical viewpoint is different from what a mathematician would consider ideal. However, the optimum design solution given in this, or any other study, considers the cost as an objective function and it can only suggest a best possible design that may be accepted, or modified after further analysis. This fact arises mainly from a reason that requirements and constraints of practical engineering are so complicated even if a good mathematical model is used.

Effect of Width of Bridge

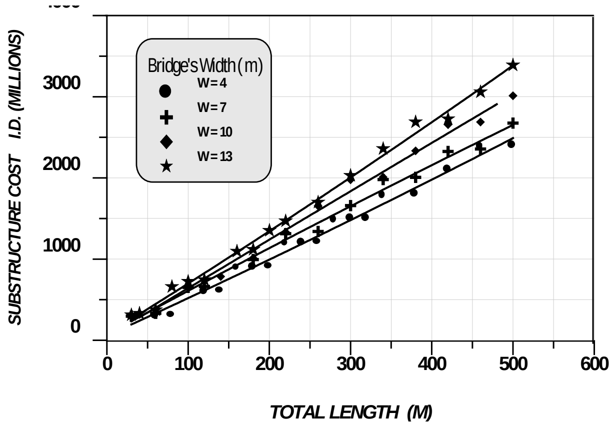

FIG. 4 RELATION BETWEEN TOTAL LENGTH AND SUBSTRUCTURE COST FOR F_Y=358 FOR STEEL AND COST RATIO (CR)=6.

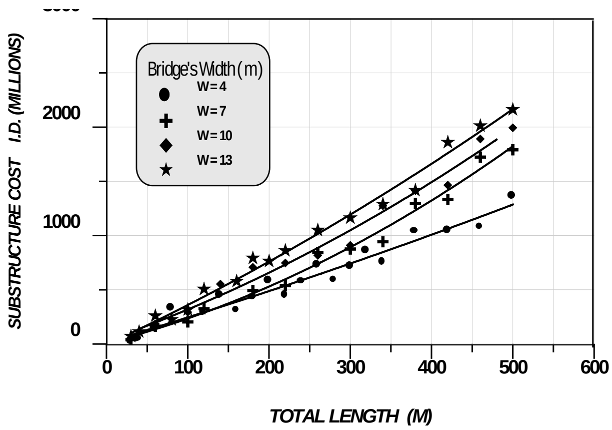

FIG. 5 RELATION BETWEEN TOTAL LENGTH AND SUPERSTRUCTURE COST FOR F_Y=358 FOR STEEL AND COST RATIO (CR)=6.

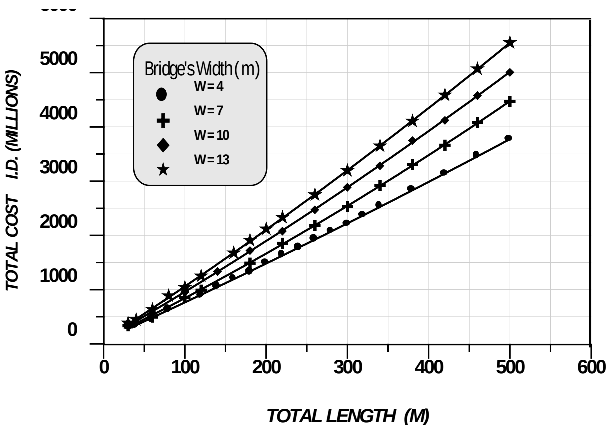

FIG. 6 RELATION BETWEEN TOTAL LENGTH AND TOTAL COST FOR FY=358 FOR STEEL AND COST RATIO (CR) =6.

FIG. 4 to FIG. 6 show that as the width of bridge increases, the cost increases proportionally.

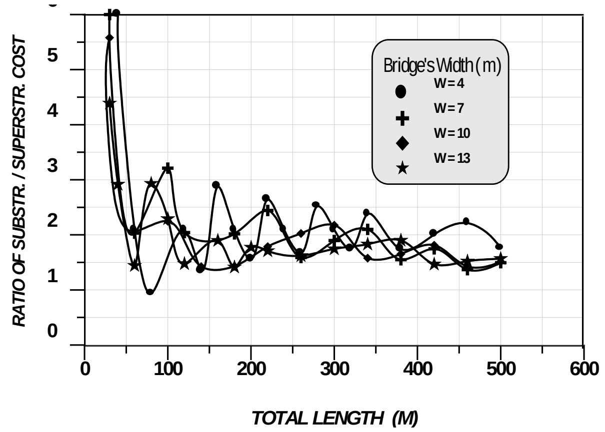

FIG. 7 RELATION BETWEEN TOTAL LENGTH AND SUB. /SUPER. COST FOR FY=358 FOR STEEL AND COST RATIO (CR)=6.

From FIG. 7, one can observe that the ratios of substructure cost to superstructure are oppositely proportioned with the width of bridges. While for specified width, sub./super. ratio becomes less if the total length of bridge increases. The curves for the widths 7, 10, 13 m become very close as the total length of the bridges increases, and one can observe this from length equal to 350 m.

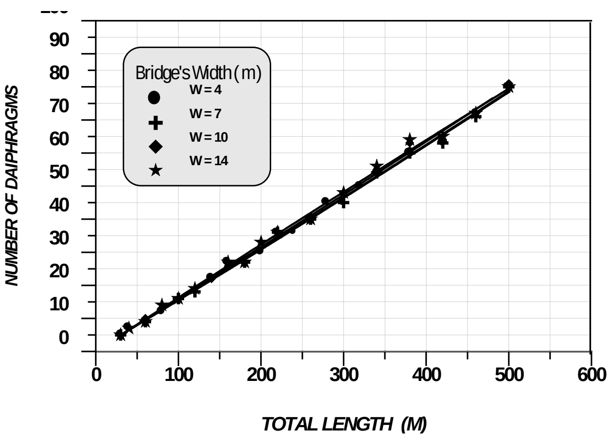

FIG. 8 RELATION BETWEEN TOTAL LENGTH AND NUMBER OF DIAPHRAGMS FOR FY=358 FOR STEEL AND COST RATIO (CR) =6.

There is no relation between width of bridge and number of diaphragms required for optimum design as shown in FIG. 8.

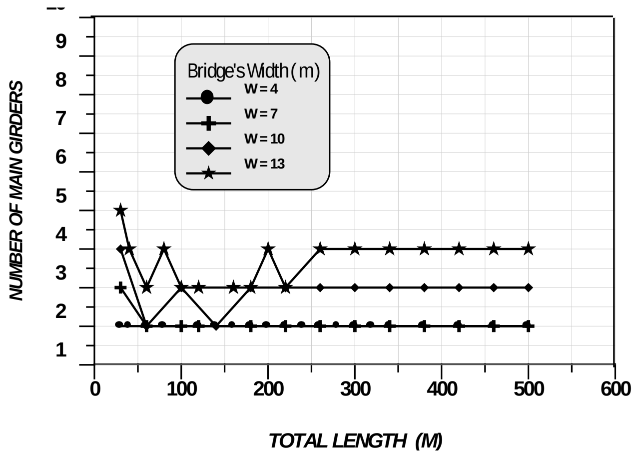

FIG. 9 RELATION BETWEEN TOTAL LENGTH AND NUMBER OF GIRDERS FOR FY=358 FOR STEEL AND COST RATIO (CR)=6.

The number of girders required becomes greater if the width of bridge increases and this behaviour is obviously correct and reasonable. The same number of girders (only two) is required when the width of bridge is between 4 m-7 m as shown in FIG. 9, while this number increases [three girders for 10 m width and four girders for 13 m width]. The diversion in the beginning of the curve belongs to the program keeping the piers as less as possible, thus it is required to increase number of girders.

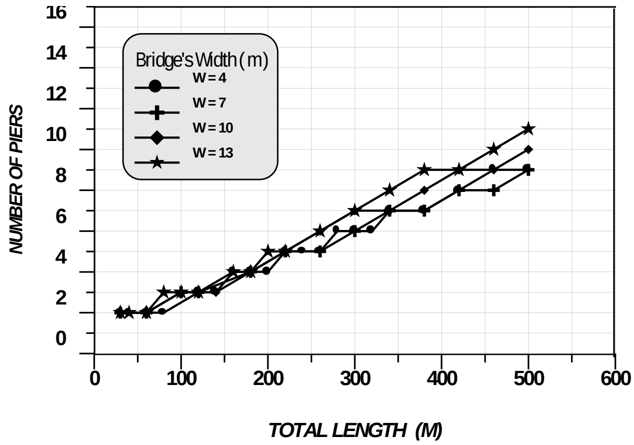

FIG. 10 RELATION BETWEEN TOTAL LENGTH AND NUMBER OF PIERS FOR FY=358 FOR STEEL AND COST RATIO (CR) =6.

The number of piers positively behaves with the width and length of the bridge, as shown in FIG. 10.

As the width of bridge increases, the optimum span length decreases and this leads to the decrement of the depth of main girder, as shown in FIG. 11 and FIG. 12. This happened because increment of the width adds more live and dead loads on the bridge, meaning that the span must be reduced to carry the applied load.

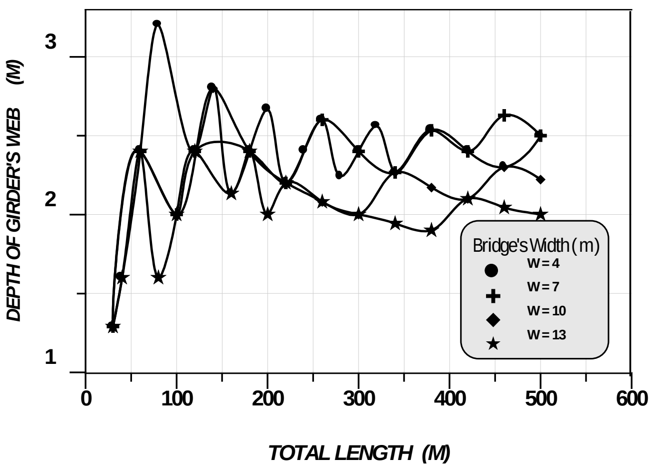

FIG. 11 RELATION BETWEEN TOTAL LENGTH AND DEPTH OF GIRDER'S WEB FOR F_Y=358 FOR STEEL AND COST RATIO (CR) =6.

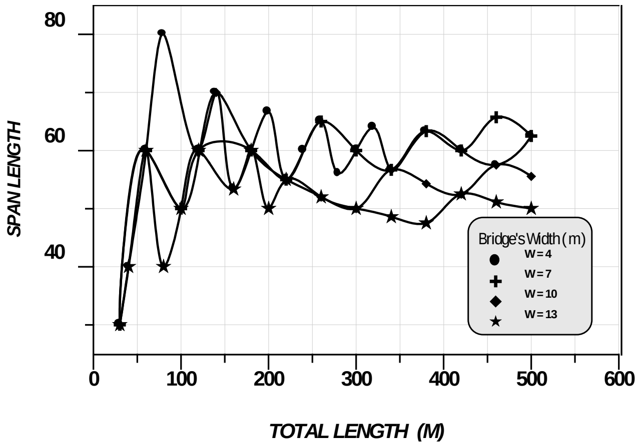

FIG. 12 RELATION BETWEEN TOTAL LENGTH AND OPTIMUM SPAN LENGTH FOR F_Y=358 FOR STEEL AND COST RATIO (CR)=6.

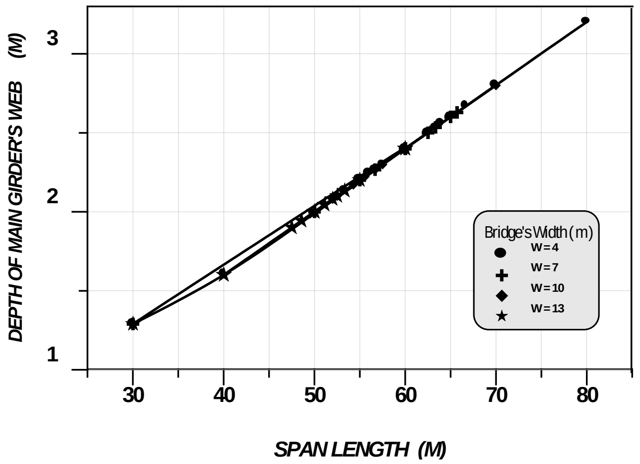

FIG. 13 RELATION BETWEEN OPTIMUM SPAN LENGTH AND DEPTH OF GIRDER'S WEB FOR F_Y=358 FOR STEEL AND COST RATIO (CR) =6.

FIG. 13 shows that there is no relation between the width of the bridge and the depth of the main girder, because the program will increase number of girders to maintain the depth of the girder within the constraints. Also there is approximately linear relation between the span length and the depth of girder, resulting from the limitations and the constraint shown above, which keeps the girder size with certain limit to give us minimum cost.

Conclusion

Based on the formulations and discussions presented in previous chapters, the following conclusions can be drawn:

1- It is found that the SUMT is a proper technique that can be used for optimum designs of steel I-girder bridges for various values of total length and width of bridges.

2- There are two factors having effect on (substructure cost/superstructure cost) ratio; and this ratio decreases, when both of bridge's width or/and bridge's total length increase. This ratio (in bridges more than 500 m length) ranges from (1.5) to (1.85).

3- In long bridges (their lengths more than 350 m), the effect of bridge's width on the ratio of substructure/superstructure is very insignificant and can be neglected.

4- There is no effect for width of bridge on the number of diaphragms used in a bridge.

5- According to this study, the optimum number of girders for a bridge ranges from 2 to 4 girders, depending on these parameters; width of the bridge, Cost Ratio CR, and the total length of the bridge, (where proportional directly with it). In general, as width increases, the main girder increases too.

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Firas I. Salman was born in Baghdad, Iraq in 1969. He has graduated from University of Technology (Baghdad) in 1990 earning B.Sc. degree in Civil Engineering, and M.Sc. degree in Structural Engineering from Baghdad University in 2004. Now he is Ph.D. student in Structural Engineering in School of Civil Engineering, Universiti Sains Malaysia, Penang, Malaysia. He has worked in different contracting and consultant companies as a civil and Sr. structural engineer in Iraq and UAE from 1992 till now.

Dr. Abdul Muttalib I. Said was born in Baghdad, Iraq in 1969. He has graduated from University of Mosul (Mosul, Iraq) in 1991 earning B.Sc. degree in Civil Engineering, Master of Science (M.Sc.) in Civil Engineering (Structures), and from Nahrian University (Baghdad-Iraq) in 1995, and Ph.D. degree in Civil Engineering (Structures) from University of Baghdad (Baghdad–Iraq) in 2000. Now he is Assistant Professor in Civil Engineering Dept., College of Engineering, University of Baghdad. He has worked as Manager of the Consulting Engineering Bureau, College of Engineering, University of Baghdad. He has Academic Activities in teaching different subjects (under-graduate courses) since 1995, Teaching post graduate studies since 2001, in addition, he has published (16) scientific papers, and supervised M. Sc. Research students (10 Students) as well as Ph.D. Research students (6 Students). He has worked as Structural designer, consultant and direction and management of the projects from 1995 till now.